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OBSERVATION OF SPICULES IN X-RAY EMISSION FROM LASER-IRRADIATED--ETC(U)
MAY 81 M J HERBST, R R WHITLOCK, F C YOUNG
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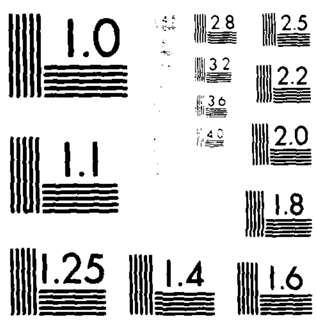

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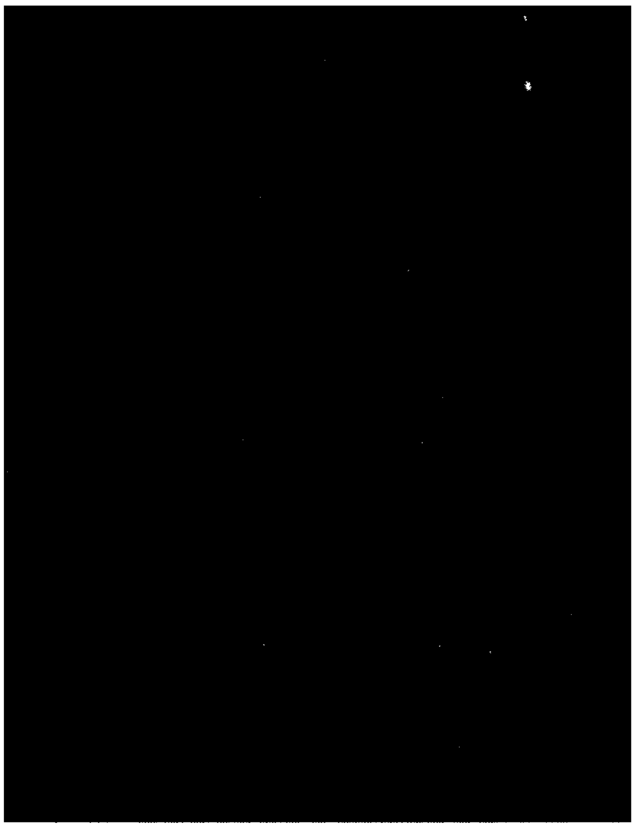

(9) Memorandum rept.,

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER (14) NRL-MR- NRL Memorandum ~~Report~~ 4437	2. GOVT ACCESSION NO. AD-A098	3. RECIPIENT'S CATALOG NUMBER 884
4. TITLE (and Subtitle) (6) OBSERVATION OF SPICULES IN X-RAY EMISSION FROM LASER-IRRADIATED TARGETS.		5. TYPE OF REPORT & PERIOD COVERED Interim report on a continuing NRL problem.
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) (10) M. J. Herbst, R. R. Whitlock, ~~and~~ F. C. Young		8. CONTRACT OR GRANT NUMBER(s) (11) 15 Mar 81
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Research Laboratory Washington, DC 20375 (12) 15		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 47-0859-0-1
11. CONTROLLING OFFICE NAME AND ADDRESS Department of Energy Washington, DC 20545		12. REPORT DATE May 15, 1981
		13. NUMBER OF PAGES 15
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Spicules
X-ray imaging
Laser-plasma interactions
Plasma instabilities

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

X-ray images of laser-irradiated solid targets show spicular structures in the blowoff plasma. Higher density is inferred in the structures, which seem to follow the fluid flow from the target. An explanation involving localized fast electron production is offered.

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OBSERVATION OF SPICULES IN X-RAY EMISSION FROM LASER-IRRADIATED TARGETS

At the high intensities ($\gtrsim 10^{15}$ W/cm^2) originally envisioned for laser fusion,[1] plasma instabilities in the pellet corona could cause large reflections of incident radiation which degrade absorption efficiency and could produce fast electrons which preheat the fuel. With much lower intensities, hydrodynamic stability of the accelerating pellet shell is a potential problem. Therefore, it has been proposed that intermediate intensities may be best for laser fusion.[2] However, the envisaged longer-pulse laser illumination will lead to larger plasmas with more gentle gradients. In these plasmas, filamentation of the incident beam may occur even at modest intensities. While the average irradiance is too low for nonlinear effects, they may grow locally due to the higher intensity in the filaments. With long-pulse, moderate-intensity illumination of flat targets, evidence for filamentation has recently been reported.[3] In the present work, evidence is found for localized effects, possibly due to the higher intensity present in the filaments.

The experimental arrangement is basically as described previously.[2] Laser pulses of 100-200J and 4-nsec (FWHM) duration from a 1.054-μm Nd laser are used to irradiate planar polystyrene (CH) targets in the near field of an f/6 lens with large diameter spots (half of the laser energy in 0.4 - 0.7 mm). This yields average intensities I_o between 3×10^{12} and 2×10^{13} W/cm^2. Pinhole camera images of time-integrated x-ray emission (photon energy E $\gtrsim$1 keV) are obtained from the rear and side of the laser-produced plasmas. With smaller focal spots (70-250μm), temporally and spatially integrated x-ray spectra (1 keV $\leq$ E $\leq$ 50 keV) are measured at higher laser intensities ($I_o \leq 7.5 \times 10^{14}$ W/cm^2) as in Ref. 2.

Manuscript submitted March 6, 1981.

Approximately half of the side-on x-ray pinhole images show fine-scale structures projecting well out in front of the target surface. These jet-like features, shown in Fig. 1A, are dubbed spicules because of their similarity in appearance to solar spicules, structures observed in XUV emission from the surface of the sun.[4] The finest observed transverse dimension of such features is pinhole resolution limited at 12 μm. From an angle of 45° to the rear, these spicules appear to emerge from small intense spots near the target surface, as shown in Fig. 1B. On most images, a much larger number of spots than spicules is observed. From many of these spots, short straight filamentary structures emanate, while just a few spots are seen to connect to fully developed spicules.

Another property of these structures is discovered by using thin targets which are ablatively accelerated[2] to speeds that allow significant target displacement during the x-ray emission (which has the laser-pulse duration[2]). Some x-rays emitted from the ablating front surface of the target are then observed from positions behind the original target location after the irradiated section is punched out from the initial target foil (see Fig. 1C). In this image, one observes fine scale striations along the direction of target motion; some of these connect to spicules observed in front of the original target position.

The angle at which a spicule emerges from the blowoff plasma depends upon its position relative to the center of the target. Spicules emanating from source points in the target plane near the center of the x-ray image propagate at angles near the target normal, while those that emerge from near the edge of the target propagate away from the target normal at larger angles. This observation is made quantitative in Fig. 2A, where spicule

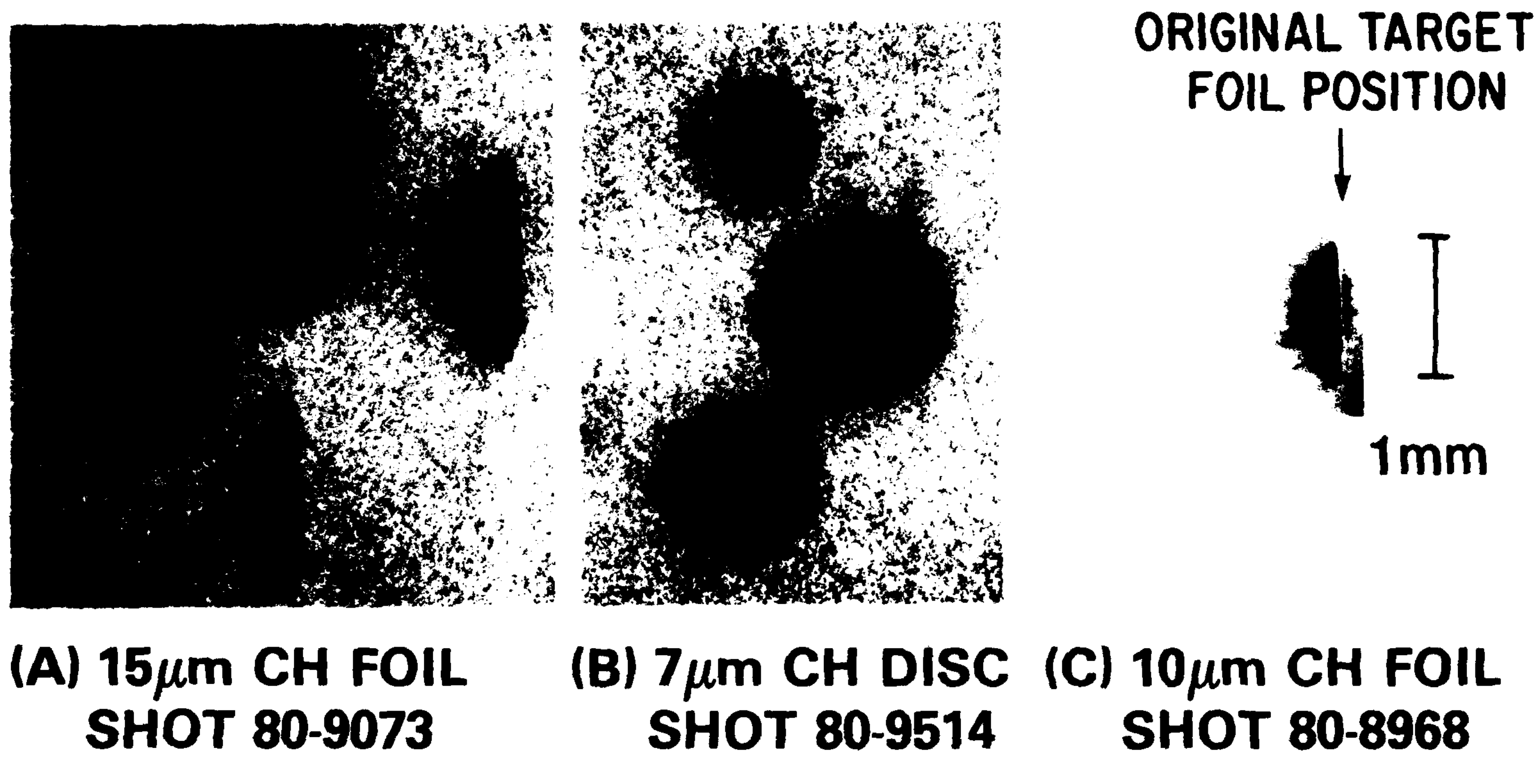

Fig. 1 — (A) Simultaneous side-on images with pinhole diameters between 8 and 55 μm. The laser is incident from left with $I_o = 5 \times 10^{12}$ W/cm^2. (B) Images from 45° to rear of disk target. The laser is directed out of the page and 45° to the right with $I_o = 5 \times 10^{12}$ W/cm^2. (C) A side view of an accelerating target at $I_o = 1.5 \times 10^{13}$ W/cm^2. The laser is incident from the left and some x-rays emanate from the accelerating target behind original foil position. The blackening in the lower right is not part of the image.

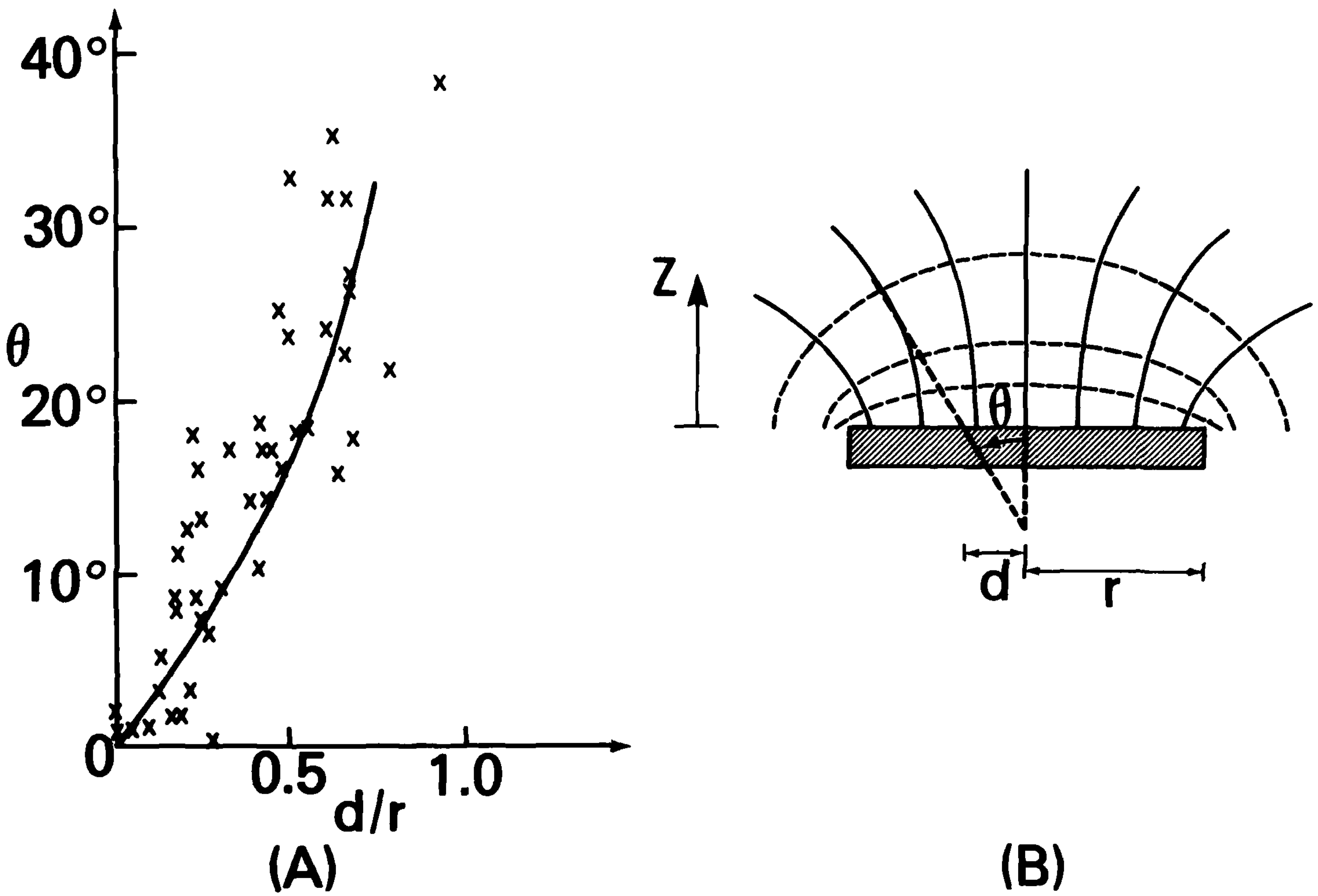

Fig. 2 — (A) Points (x) are spicule tangent angles θ relative to target normal (at $z = r/2$) as function of spicule displacement d at target surface (plotted data is from 25 laser shots). Curve is for flow field of Fig. 2B. (B) Flow lines (—) and equipotential lines (---) for Laplacian fluid flow.

angles relative to the normal are plotted as a function of the displacement from the center of the image. Displacements are measured between target center and the intersection between the tangent to the spicule and the target surface (see Fig. 2B). Due to spicule curvature, these vary with distance z from the target surface; for Fig. 2A, a fixed $z = r/2$ is used.

From the distribution of spicule angles (Fig. 2A), we infer that spicules follow the fluid flow from the target. The pattern of fluid streamlines from planar targets has been shown to resemble a Laplacian field, shown in Fig. 2B, of steady-state fluid flow at low Mach number from a circular nozzle.[5] The dependence of streamline angle upon lateral displacement for this Laplacian flow, with the angle and displacement as defined above, is the curve in Fig. 2A. Similarity between the curve and the spicule data is noted.

The x-ray images of the CH targets include only continuum emission because the Be filters exclude carbon and hydrogen lines. If a thermal spectrum at temperature T is assumed, the emitted continuum intensity varies as $\exp\left[-E/T\right]$. A color temperature is then obtained for both the spicule and surrounding blowoff plasma by simultaneous imaging with two cameras, filtered differently to give low energy cutoffs near 1 and 3 keV, respectively. A computer model[6] of the measured absolute film sensitivity[7] is used to match the ratio of the two exposures with a best-fit thermal spectrum. For both the spicule and blowoff plasmas, the temperatures are 400 ± 20 eV, in agreement with temperatures obtained from measured x-ray spectra (see Fig. 3A).

The spicules are localized, more intense and therefore more emissive than the larger blowoff. Since equal spicule and blowoff temperatures are obtained from the two-color x-ray images, higher spicule emissivity implies locally higher density. We now propose three possible mechanisms to explain the observations. First, if cold, solid-density material were ejected from near the target surface, its path through the blowoff could trace out a spicule-shaped image in a time-integrated photograph, and bombardment by plasma electrons would lead to cold-target bremsstrahlung with a spectrum characteristic of the plasma temperature. This explanation is unlikely because the conversion efficiency from electron energy to x-rays[8] by a 400-eV plasma is too small to explain the locally higher emissivity.

A second possibility is that direct laser illumination of the solid target surface locally increases mass ablation rates, generating higher density regions in the blowoff plasma. This could result, for instance, if low-density channels in the incident-light path, due to filamentation, provide a locally underdense path by which the laser may tunnel through the overdense plasma to the target surface. Since the fluid-flow path of this dense material differs from the incident-light path, the low-density channels are not destroyed by the higher density material. However, this explanation requires secondary mechanisms, perhaps a magnetic field, to: 1) prevent lateral conduction at the target surface from smearing out the locally deposited laser energy, and 2) prevent disassembly of the higher density structure as it follows the fluid flow from the target. One would also expect to burn through the target locally; no evidence for this is found either in side-on x-ray images or in studies of target acceleration.[9]

The third explanation also depends upon filamentation for generation of the high-density regions, but is more promising since it also provides for maintaining that higher density. We speculate that a fast electron current produced locally due to the higher intensity in the filaments can create sufficient magnetic field to constrict a portion of the blowoff and increase the density locally. The magnitude of the required magnetic field B depends upon the ratio of the electron density in the spicule to the nearby blowoff density. In the region of most intense blowoff x-ray emission, this ratio is estimated from the relative intensity and chord length of the spicule to be three, if the durations of emission from spicule and blowoff are equal. We estimate the required confinement field B to be 4.5 MGauss at the measured temperature and at density $n = 3n_c$ (since thermal x-ray emission is expected to peak near the region of critical density n_c[10]). Megagauss fields have been observed in laser-produced plasmas, though at higher intensity.[11] If the duration of x-ray emission from the spicules is less than that from the blowoff, or if the region of strongest x-ray emission has $n > n_c$, then the inferred spicule density and B are higher. However, if the x-ray emission from the spicules is due to thermal plasma bombardment of colder plasma (as opposed to cold solid material, as rejected earlier), a lower value of B is required.

Support is lent to the above hypothesis if spicule observations are correlated with the presence of fast electrons as detected by nonthermal x-ray emission. However, the expected energetic-photon flux if fast electrons are present only in the spicule volume is well below detectable levels for our instrumentation. Instead, we establish plausibility of the model by detecting fast electrons at decreased laser spot sizes, with whole-beam intensities comparable to what may exist in self-focused hot spots. With $I_o > 3 \times 10^{12}$ W/cm^2, 2:1 laser intensity modulation, and inferred reductions in hot-spot dimensions due to self-focusing by factors of 4 to 16,[3] self-focused hot-spot intensities I_h exceed 10^{14} W/cm^2. With whole-beam intensity $I_o > 10^{14}$ W/cm^2, emission by fast electrons is observed in x-ray spectra (Fig. 3B). If the flow of electrons is directed, as has been suggested by experiments,[12,13] a net current flow and confining magnetic field result.

Further support for the model is obtained by comparing the hot electron density n_H inferred from the x-ray spectral measurements with that required to generate B = 4.5 MGauss around a spicule. To calculate the latter, we note that a suprathermal electron temperature $T_H \simeq 10$ keV is deduced from Fig. 3B. If the current density J_H of these directed fast particles is to produce B around a cylinder of radius r_o, then $J_H = n_H eV_H = 2B/\mu_o r_o$. Here, $\overline{V}_H = (2 T_H/m)^{\frac{1}{2}}$ is the hot electron thermal velocity, e and m are the electron charge and mass, and μ_o is the permeability of free space. With B = 4.5 MGauss and T_H = 10 keV, one obtains $n_H \simeq 0.01\ n_c$ if r_o = 10 μm.

To infer an n_H from the x-ray spectra, we assume that suprathermal x-rays are produced by thick-target bremsstrahlung[8] due to energetic electron bombardment of cold target material. We further assume that: 1) the electrons are monoenergetic with energy T_H, 2) the electron flux impacts an area of cold target surface equal to the focal spot area, 3) the duration of the suprathermal emission is equal to that of the thermal emission, and 4) the suprathermal emission is isotropic. With these assumptions, the ratio n_H/n_c is found to have the values 10^{-4} and 5×10^{-3} at $I_o = 10^{14}$ W/cm^2 and 7.5×10^{14} W/cm^2, respectively. To create local regions with $I_h > 7.5 \times 10^{14}$ W/cm^2, incident-laser hot-spot dimensions must be reduced by factors of 4 to 10, which is consistent with inferred reductions due to filamentation.[3] Therefore, it is plausible that $n_H \simeq 0.01\ n_c$

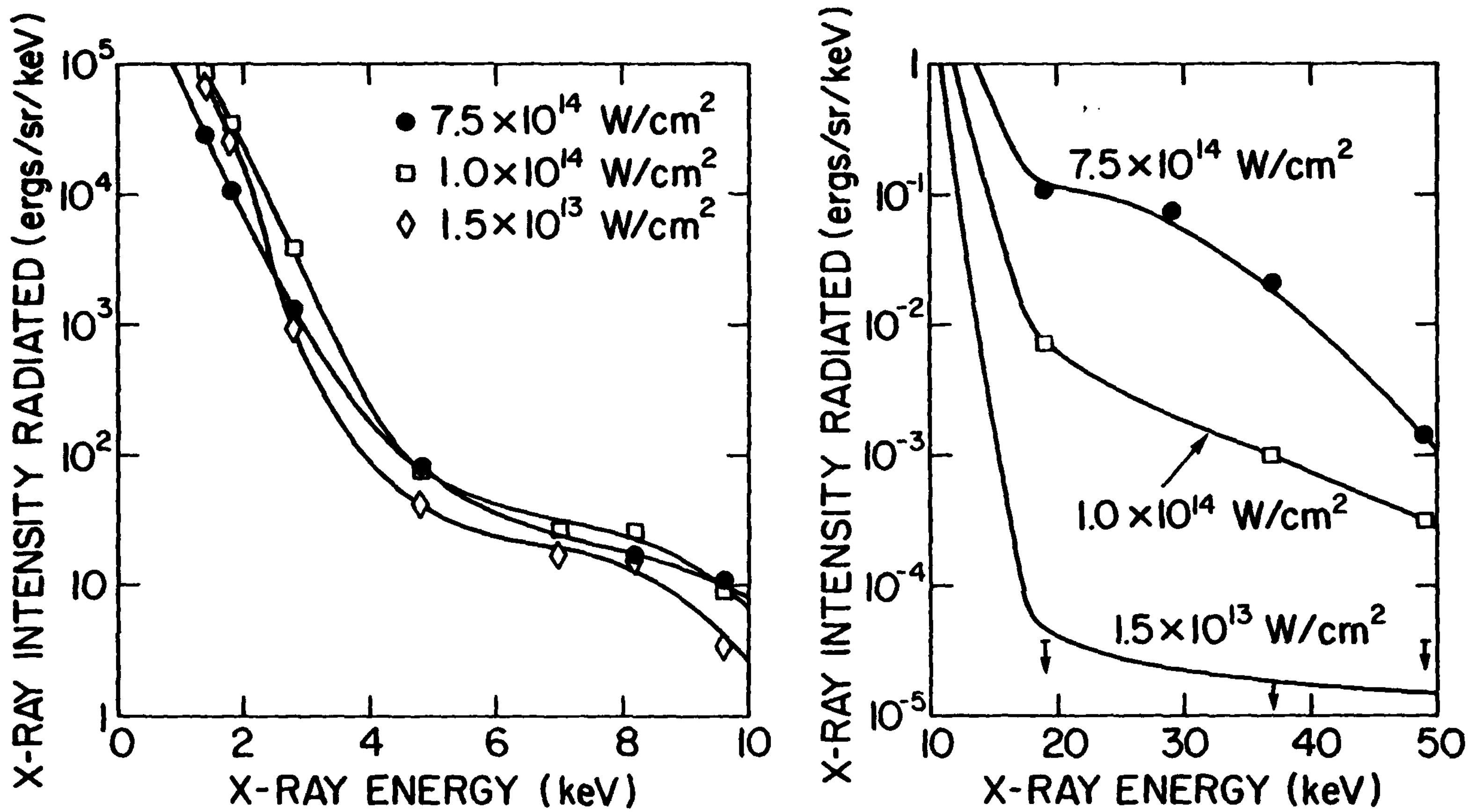

Fig. 3 — Spatially and temporally integrated x-ray spectra measured at three average irradiances (spot sizes) on planar CH targets with laser energy nearly constant at 200J. (A) Low energy region with temperature of 0.3-0.4 keV in the 1-4 keV range. (B) High energy region with temperatures of 8-10 keV in the 20-50 keV range. At the lowest irradiance no x-rays with energy greater than 10 keV are detected.

locally, which could produce the required J_H.

One should note that the measurement of a color temperature in the spicule equal to that in the blowoff does not preclude the presence of fast electrons in the spicule since the fast-electron population has no effect on the spectral shape below 5 keV (see Fig. 3). Whether nonthermal electrons are present in the spicules is not yet established because the small fluxes of energetic photons cannot be imaged with the present detection system.

A self-consistent, if not unique, explanation for the spicules, then, is that localized fast electron currents in regions of higher irradiance cause magnetic fields which constrict portions of the blowoff in a manner similar to the Weibel instability.[14] Experimental evidence is found for the required fast electrons if the local intensity is increased by filamentation. These spicules seem to follow the fluid flow from the target and appear to connect to striations in the thermal x-ray emission observed behind the original foil position for accelerated targets.

The authors acknowledge useful conversations with Drs. S.E. Bodner, R.H. Lehmberg, S.P. Obenschain, and B.H. Ripin as well as the technical assistance of M. Fink, R. McGill, N. Nocerino, L. Seymour, E. Turbyfill and A. Unzicker. The authors are also grateful for contributions of J.W. Criss to computer coding for the two-color imaging. This work was supported by the U.S. Department of Energy and Office of Naval Research.

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